Study of Aberrations at the Focus of an Ultrasonic Beam due to the Propagation Across Different Areas of the Skull

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Background

Introduction

Some neurodegenerative diseases as Alzheimer's or Parkinson's are supposed to be treated by using focused ultrasound therapy and microbubble injection, aiming the BBB (Blood Brain Barrier) opening to have access to concrete zones of brain and then to effectively deliver therapeutical drugs.

This study addresses the transcranial targeting of whatever part of human brain, but specially taking into account normal skull surface incidence through occipital, right temporal and top parietal zones, in order to analyze the ultrasound beam aberrations like attenuation, focus position deviation and focus width, employing a focused transducer working at 500 kHz.

The Matlab toolbox k-Wave is used for time domain ultrasound 3-D fluid media simulations with CT-based acoustic maps of a human skull.

Main objectives:

- Development of a geometrical algorithm to locate the transducer in order to generate a normal incidence beam with the skull.
- Analysis of the focus properties (attenuation, displacement and FWHM) when the beam propagates through the occipital, temporal and parietal skull zones depending on the angle of incidence: 0º, 5º, 10º, 15º and 20º respect to the axial direction of the transducer.
- Analysis of the focus properties depending on the separation distance between transducer and skull propagating through the occipital zone.

Model equations

k-Wave Matlab toolbox is based on the k-space pseudospectral method.

- The coupled governing equations are combined resulting a modified form of the Westervelt equation:

$$\nabla^2 p - \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} - \frac{1}{\rho_0}\nabla\rho_0 \cdot \nabla p + \frac{\beta}{\rho_0 c_0^4}\frac{\partial^2 p^2}{\partial t^2} - L\nabla^2 p = 0$$

where:

» $\beta = 1 + \frac{B}{2A}$ is the coefficient of nonlinearity
» L is a general loss operator

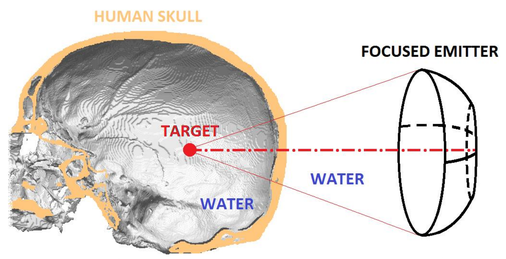
- Power law absorption:

$$\alpha = \alpha_0 \omega^y$$

Materials and Methods

Boundary conditions

Medium formed by skull, water and focused emitter transducer. For simplycity, brain properties (sound speed, density and absorption) have been simulated as if they were water.



CT scans obtaining apparent density 3D mapping of skull and water medium:

- Sound speed
- Density
- Attenuation
- Resolution = 0.501 mm

- f_0 = 500 kHz
- Focal length= 100 mm
- Transducer aperture = 90.5 mm
- Hole radius = 17 mm
- Initial pressure = 0.1 MPa
- Gain = 24.95 dB

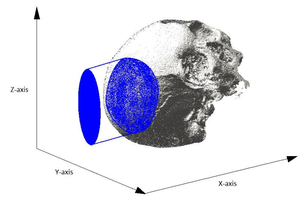
Rotation method for normal incidence

This method allows accurate rotation of skull in order to have normal incidence, and also lets the user select the separation distance between transducer and skull.

General idea:
1. Obtain normal vector of transducer.
2. Obtain normal vector of targeted skull surface.

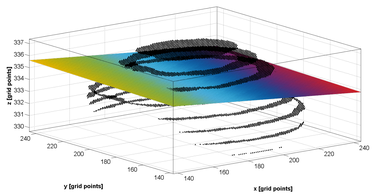
Match the direction and sense of both vectors.

- First, skull surface reached by ultrasound beam is obtained. Initially, this surface could be normal or not to the direction of propagation of the beam.



Obtaining the skull surface reached by ultrasound beam by projecting onto skull the equivalent area covered by the beam.

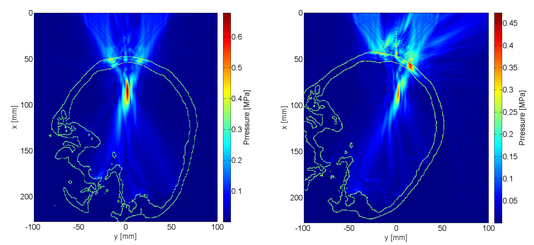
- Then, the algorithm fits the obtained skull surface to a plane, after that calculates rotation angles and finally applys accurate traslation and rotation to locate skull properly.



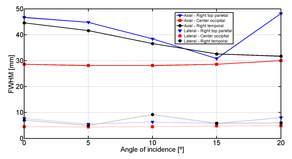
Fitting the skull surface to a plane to obtain its normal vector; black points represent skull surface reached by ultrasound beam.

Results

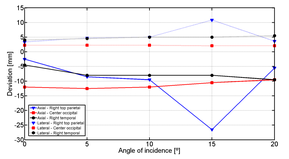
Depending on angle of incidence



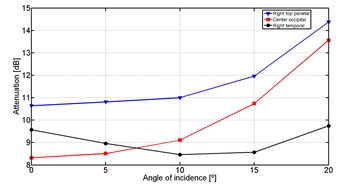
Propagation through the center occipital zone; normal incidence (left) and 20º of incidence (right).



Axial and lateral FWHM of the beam focus propagating through different skull zones.

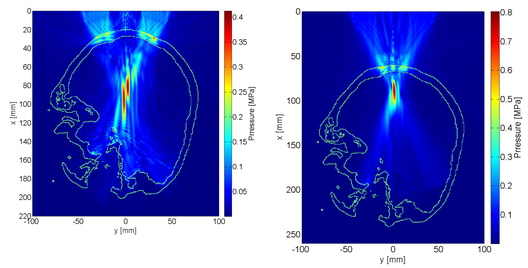


Axial and lateral deviation of the beam focus propagating through different skull zones.

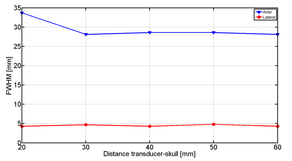


Focus attenuation propagating through different skull zones.

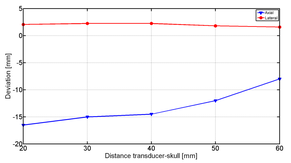
Depending on distance to transducer



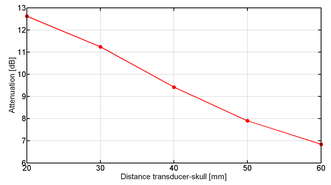
Normal incidence propagation through the center occipital zone; distance transducer-skull of 20 mm (left) and 60 mm (right).



Axial and lateral FWHM of the beam focus propagating through the center occipital zone.



Axial and lateral deviation of the beam focus propagating through the center occipital zone.



Focus attenuation propagating through the center occipital zone.

Conclusions

- Refraction of the ultrasonic waves in the skull has shown to play an important effect on the axial displacement of the beam focus. It can go from -2 to -15 mm depending on the area, angle and distance of incidence. It seems it is not strongly affected by the angle of incidence when it is lower than 10 degrees. Nevertheless, the area of incidence (occipital, parietal or temporal) can change considerably the shift value. Also, to bridge the gap between the transducer and the skull increases the axial displacement of the focus, as we are increasing the interaction volume between the beam and the skull.
- Lateral deviation of the focus provides information about the non axysimmetry of the skull. These values change between 2 and 5 mm and they look quite stable with angle incidence and transducer-skull distance.
- Axial and lateral FWHM present different behavior depending on the incidence zone. The occipital zone shows the shortest axial FWHM, 30 mm, even shorter than the axial FWHM of the focus in water (38.5 mm). This can be due to a focusing effect of the skull, but it could also be due to a local effect. Lateral FWHM remains stable in values between 5 and 9 mm, slightly higher than in water (4.4 mm).
- As it seems logical, the attenuation of the transcranial propagation increases when the incident angle increases, as the transmission factor decreases with the angle. Attenuation increases also when the distance transducer-skull is lower, as the beam cross a higher volume of skull.
- Although several trends can be found in this study, local heterogeneities in the area where the ultrasound beam crosses the skull have shown to affect drastically the location and the quality of the focus. To validate most of the present conclusions more simulations should be done in each area, as well as in different CTs.
- Other parameters, as the number of focuses produced in the transcranial propagation or the acoustic energy deposited in a defined volume should be incorporated in future studies.

Aknowledgments

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